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SUITABILITY OF CARBON RESISTORS FOR FIELD MEASUREMENTS OF TEMPERATURES IN THE RANGE OF 35° TO 100° R

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E-233

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SUITABILITY OF CARBON RESISTORS FOR FIELD MEASUREMENTS OF TEMPERATURES IN THE RANGE OF 35° TO 100° R

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SUMMARY

Material is presented for using a carbon composition resistor to measure temperature in the range of 35° to 100° R to an accuracy of 1 percent of the absolute temperature. The important characteristics of the resistor as a sensing element are discussed together with circuitry especially suited to field-type instrumentation.

INTRODUCTION

Research in the use of liquid hydrogen as a rocket fuel introduced many new instrumentation problems. One of these was the measurement of the extremely low temperatures involved. Practical considerations limit the field use of the usual means of temperature measurement. The decreased sensitivity of the thermocouple at low temperatures as well as the noise level of long lines and the limit of sensibility of the detecting system may cause large errors in temperature measurement. The limitation in the use of platinum resistance thermometers comes about because of the low value of resistance at low temperatures of the common thermometer resistance values (25 to 100 ohms at 0° C). Lead resistances may be very much higher than the bulb resistance, requiring rather complicated circuitry, which might be impractical if large numbers of bulbs are used. Vapor pressure and gas thermometers are limited as to reduction in bulb size and involve systems that must remain intact.

The need for a small, simply instrumented, sensitive thermal element for low temperature measurement is fulfilled by certain types of semiconductors. Various references in the literature relate how carbon composition resistors have been used successfully for accurate temperature measurements from about 4° to 37° R. The work of Clement and Quinnell (ref. 1) rather thoroughly covered temperature measurement in this range using 1-watt Allen-Bradley resistors. Templeton and MacDonald (ref. 2), in their investigation of 1/4-watt Erie resistors as thermal noise sources at low temperatures, determined the temperature-resistance relation from 20° to 500° R as well as the effect of pressure on resistance.

This investigation was begun to determine whether a carbon composition resistor could be used for field measurements. The literature indicated that sensitivity would be adequate. The question of stability under the operating condition encountered in the field needed to be determined. After preliminary tests, a 100-ohm 1/10-watt commercial resistor was chosen. The thermal sensitivity of the resistor is high, its small size is well suited to mounting in test apparatus, and the relatively low resistance results in a satisfactory impedance for instrumentation. More extensive tests were begun to determine the stability of calibration under conditions of temperature cycling as encountered in field operations. The effect of pressure on the temperature-resistance relation, the necessary limitation of measuring current due to self-heating effects, and the response time were also investigated.

Various methods of measuring resistance were tried. One simple bridge circuit is described in the appendix.

APPARATUS AND PROCEDURE

In order to establish a temperature-resistance relation, approximately 40 resistors were calibrated in groups of 10 in the apparatus shown in figure 1. An NBS-certified platinum resistance thermometer served as a standard for measuring temperatures to within 0.1° R. Taped midway around the platinum thermometer bulb, the carbon resistors were connected in series, and an 8-inch manganin potential lead was soldered to each junction. Manganin current leads as well as potential leads were attached to each end of the series. Manganin was selected because of its low relative thermal conductivity in order to minimize heat leak through the leads. This assembly was inserted and sealed in a copper equalizing bar on which a resistance-wire heating element was wound. The unit was centered and thermally isolated in a sealed brass cell located in the lower part of a Dewar flask. The flask was sealed in a larger brass container within another wide-mouthed Dewar.

The manganin leads from the carbon resistors and from the platinum resistance thermometer were wrapped several times around the copper equalizer and soldered to individual 30-gage enameled copper leads. These were brought up through a tube to hermetically sealed terminals and thence to a connector on the terminal box. Copper leads from the heating element also were brought out in this manner. The tube containing the leads was provided with a tap to permit evacuating or filling the test cell.

Separate d-c sources were set up to supply 2 milliamperes for the platinum resistance thermometer and 100 microamperes for the carbon resistor series. Appropriate precision resistors were included in both circuits to furnish reference potentials for comparative measurements. Potential leads were extended to a selector switch and thence to a precision laboratory potentiometer. A low-voltage transformer with variable input supplied current to the heater as required.

Measurements were made with normal and reversed currents in order to nullify the effects of any random thermal electromotive forces in the circuits. After readings at normal temperature had been obtained, the test cell was purged by evacuation and charged with helium. The outer Dewar was filled with liquid nitrogen to cool the inner Dewar, which was then filled with liquid hydrogen. When the test unit reached an equilibrium temperature very near that of liquid hydrogen, measurements were made as before. In subsequent steps the test cell was evacuated continuously and the test unit was raised to various temperature levels above that of liquid hydrogen by passing current as required through the heater. Temperatures above 110° R were obtained with the inner Dewar filled with liquid nitrogen and the shell of the inner container removed to expose the test unit directly to the liquid. Temperature levels were obtained with various stages of pressure reduction within the Dewar. Temperature and resistance measurements were made at each level after equilibrium had been obtained.

Pressure effects were measured with a small stainless-steel cylinder capable of withstanding an internal pressure of 1000 pounds per square inch at 36° R. The cylinder, containing five resistors, was immersed in a liquid-hydrogen bath and pressurized in steps to 1000 pounds per square inch with hydrogen gas in some tests and helium in others. Sufficient time elapsed at each pressure step to allow the resistors to reach the temperature of the liquid-hydrogen bath.

To determine the self-heating effects of current through the resistor, resistance was measured at various current levels in both hydrogen gas and liquid hydrogen at approximately 36° R. The resistors were placed in a sealed container immersed in liquid hydrogen boiling at atmospheric pressure. By evacuating the container and filling it with hydrogen gas at slightly less than atmospheric pressure, a hydrogen-gas atmosphere was maintained inside the container. Slight pressurization with hydrogen gas filled the container with condensed liquid hydrogen.

An estimate of the speed of response of the resistor was obtained by immersing the resistor at room temperature into a bath of liquid hydrogen and recording the resistance against time on an oscillograph. Since in use the resistors must be mounted in some type of holder, the response tests were repeated on the two types of probes shown in figure 2. Another series of tests was carried out with the probes mounted in a line carrying liquid hydrogen at velocities of 100 feet per second and 800 pounds per square inch.

RESULTS AND DISCUSSION

The nominal value of the resistors is 100 ohms ±5 percent at ambient temperature. Resistor ratios (R_H/R_N) range from 2.30 to 2.50, where R_H is the resistance at normal hydrogen boiling point and R_N is the resistance at 540° R. The absolute value of a resistor and its resistance ratio may vary with time. The change in ratio is much less than the change in absolute resistance.

Figure 3 is a plot of R_T/R_N against the reciprocal of the absolute temperature for a typical resistor using two calibration points, 540° R and the normal boiling point of hydrogen (R_T is the resistance at any temp. T). All resistors do not follow the same straight line but fall on one of a family of curves whose limits are shown by the dashed lines. Using such a calibration plot to measure temperature requires adding temperature corrections as shown in figure 4.

If a group of resistors is not calibrated and a ratio of 2.4 is assumed, the variation in ratio of 97 percent of the resistors will be within ±0.06, or 3.5 percent of the absolute temperature. If the same group of resistors is calibrated once, 95 percent of the resistors will have a limit of error in the ratio of ±0.016, or 1 percent of the absolute temperature. A better method is to check resistors for five readings at weekly intervals at both room temperature and the normal hydrogen boiling point. If any resistor whose ratio deviates more than ±0.007 is eliminated, the limit of error for a 4-month period after checking is ±0.012, or 3/4 percent of the absolute temperature. The stability results were obtained on a sample of 100 resistors on which approximately 2300 readings were taken over a 9-month period.

Mounting of resistors may cause instability due to handling and heating from soldering. Therefore, the resistor checking procedure should be repeated after installation whenever possible.

Since the resistance ratio is much more constant than the absolute resistance, a measuring system directly dependent on the ratio should be used. The circuit shown in figure 5 and described in the appendix is especially suited to temperature measurements.

Tests were made on approximately 25 resistors to determine the pressure effect. As pressure on these resistors increases, resistance decreases proportionally. The resistance decreases about 1 percent at 1000 pounds per square inch. Since thermal sensitivity varies with temperature, a pressure of 1000 pounds per square inch will cause the following errors in indicated temperature:

1 percent at 36° R, or 0.36° R

2.5 percent at 100° R, or 2.5° R

E-233

Since the output signal is a function of resistor current as well as resistance, it may be desirable to use maximum allowable current. Limitation of the current is imposed by self-heating in the resistor. The relation between resistor current and heating error for static immersion in liquid hydrogen and in gas at atmospheric pressure is shown in figure 6.

The determination of the thermal response time of a resistor is rather uncertain because of variation in heat-transfer conditions. The bare resistor requires about 2 seconds to reach final temperature on direct immersion, but under the same conditions the fastest probe requires about 9 seconds. The open probe requires about 6 seconds under the high-pressure, high-velocity conditions, while the closed probe requires 11 seconds.

CONCLUSIONS

Carbon resistors such as the type used in these tests are well suited to the field measurement of temperatures in the range 35° to 100° R within 1 percent of the absolute temperature. Pressure effects on temperature readings are reproducible and can be corrected. The change in absolute resistance with time will be troublesome unless the circuitry used in the system bases the temperature reading on the resistance ratio rather than the absolute resistance value. After the relation of resistance and temperature has been established for a sample of resistors, routine calibration of others requires measurements at only two temperatures. Readings can be taken at room temperature and at the atmospheric boiling point of liquid hydrogen.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, November 13, 1959

APPENDIX - CIRCUITRY

The circuit of figure 5 may be used to measure temperature using carbon resistors. It can be shown to be independent of lead resistances R_L and has good sensitivity with low bridge current. The bridge-probe combination can be calibrated in the field if the ratio R_H/R_N is known. The output voltage is very nearly proportional to the ratio $(R_T/R_N) - 1$. Although the ratios for each probe are difficult, the outputs will follow a standard curve.

From figure 5(a),

$$e_0 = R_T(i_3 + \Delta i_3) - r(i_2 + \Delta i_2) = R_T i_3 \left(1 + \frac{\Delta i_3}{i_3}\right) - r i_2 \left(1 + \frac{\Delta i_2}{i_2}\right) \quad (1)$$

where i_2 and i_3 are the currents when $R_T = R_N$, and $(i_2 + \Delta i_2)$ and $(i_3 + \Delta i_3)$ are the currents when $R_T \neq R_N$.

Since $r i_2 = R_N i_3$,

$$e_0 = \frac{R_T}{R_N} R_N i_3 \left(1 + \frac{\Delta i_3}{i_3}\right) - R_N i_3 \left(1 + \frac{\Delta i_2}{i_2}\right) \quad (2)$$

From figure 5(c),

$$E = R_1(i_3 + i_2) + R_2 i_2$$

$$R_2 i_2 = R_3 i_3$$

$$i_3 = \frac{ER_2}{R_1(R_2 + R_3) + R_2R_3}$$

$$\frac{\Delta i_3}{i_3} = -\frac{\Delta R_3(R_1 + R_2)}{R_1(R_2 + R_3) + R_2R_3} \approx -\frac{3}{4}\frac{R_T - R_N}{R}$$

$$i_2 = \frac{ER_3}{R_1(R_2 + R_3) + R_2R_3}$$

$$\frac{\Delta i_2}{i_2} = \frac{\Delta R_3 R_1}{R_1(R_2 + R_3) + R_2R_3} \approx \frac{R_T - R_N}{4R}$$

E-233

Letting $R_N i_3 = e_c$, and substituting for $\frac{\Delta i_3}{i_3}$ and $\frac{\Delta i_2}{i_2}$,

$$e_0 = \frac{R_T}{R_N} e_c \left(1 - \frac{3}{4} \frac{R_T - R_N}{R}\right) - e_c \left(1 + \frac{R_T - R_N}{4R}\right)$$

$$= e_c \left[\left(\frac{R_T}{R_N} - 1\right) - \frac{R_T - R_N}{4R}\left(\frac{3R_T}{R_N} + 1\right)\right]$$

At atmospheric boiling point of liquid hydrogen, $R_T = R_H$, and

$$e_{0,H} = e_c \left[\left(\frac{R_H}{R_N} - 1\right) - \frac{R_H - R_N}{4R}\left(\frac{3R_H}{R_N} + 1\right)\right]$$

Letting $K = \left[(R_H/R_N) - 1\right]$,

$$e_0 \approx \frac{e_{0,H}\left(\frac{R_T}{R_N} - 1\right)}{K}\left(1 - \frac{3}{4}\frac{R_T - R_H}{R}\right)$$

$$e_c = \frac{e_{0,H}}{K}(1 + \epsilon)$$

where $\epsilon = \frac{R_N(3K + 4)}{4R}$.

Typical values of ϵ are as follows:

ϵ	R
0.004	50K
.003	75K
.002	100K

If $e_{0,H}$ is 95 percent of full-scale, figure 7 shows output against temperature for the circuit of figure 5.

To field-calibrate the bridge, with the probe at 540° R, the RUN-CAL switch is in the CAL position and the supply voltage and R_S are adjusted until the output voltage equals e_c. In the RUN position the zero potentiometer is adjusted for zero output. To calibrate at any other temperature, a correction must be added to e_c as shown in figure 8. After the current is adjusted, the zero potentiometer is adjusted with the switch in the RUN position until the output voltage is equal to the correction voltage.

REFERENCES

1. Clement, J. R., and Quinnell, E. H.: Low Temperature Characteristics of Carbon-Composition Thermometers. Rev. Sci. Instr., vol. 23, no. 5, May 1952, pp. 213-216.

2. Templeton, I. M., and MacDonald, D. K. C.: The Electrical Conductivity and Current Noise of Carbon Resistors. Proc. Phys. Soc., sec. B, vol. 66, Aug. 1953, pp. 680-687.

E-233

CF-2

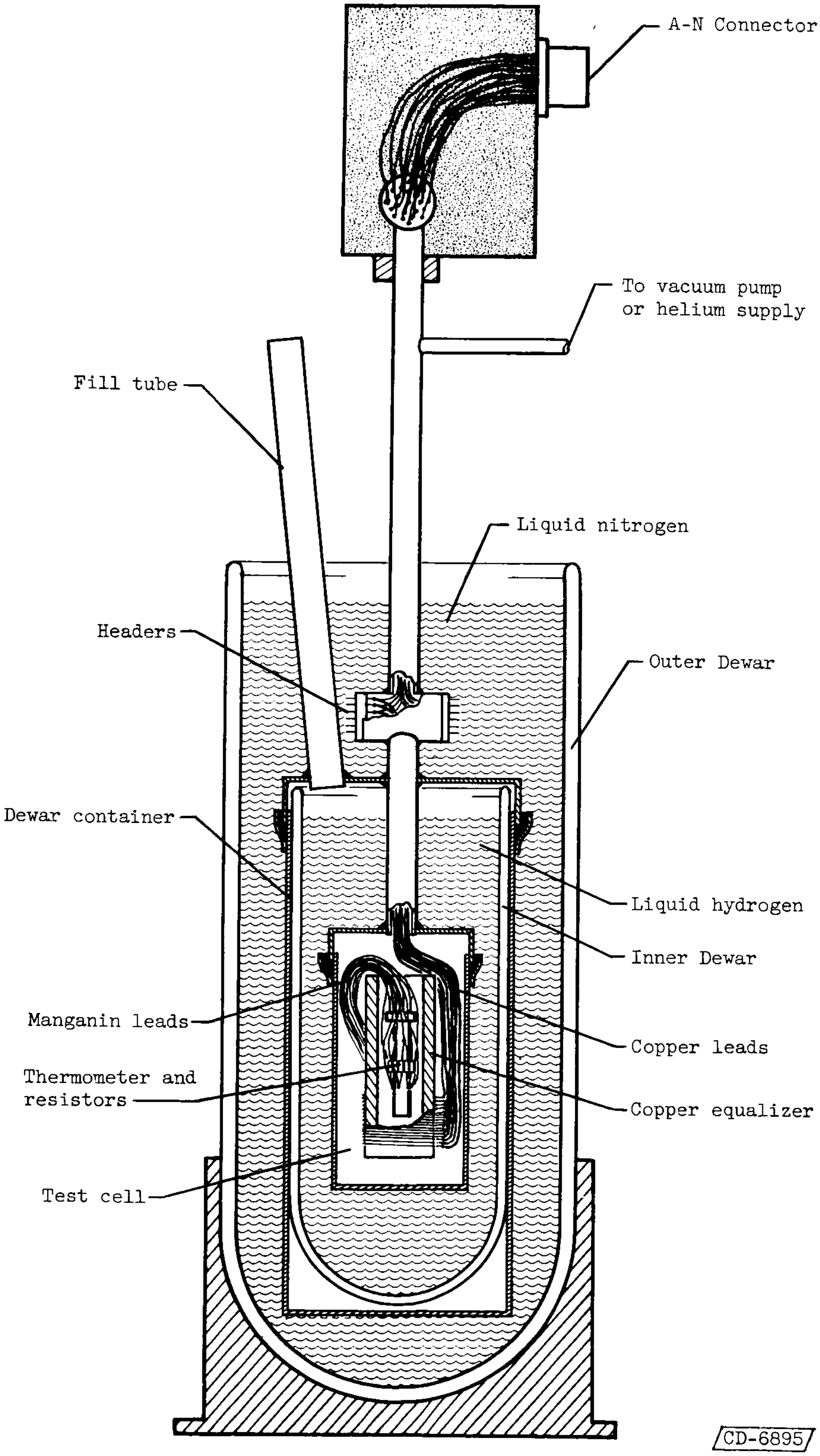
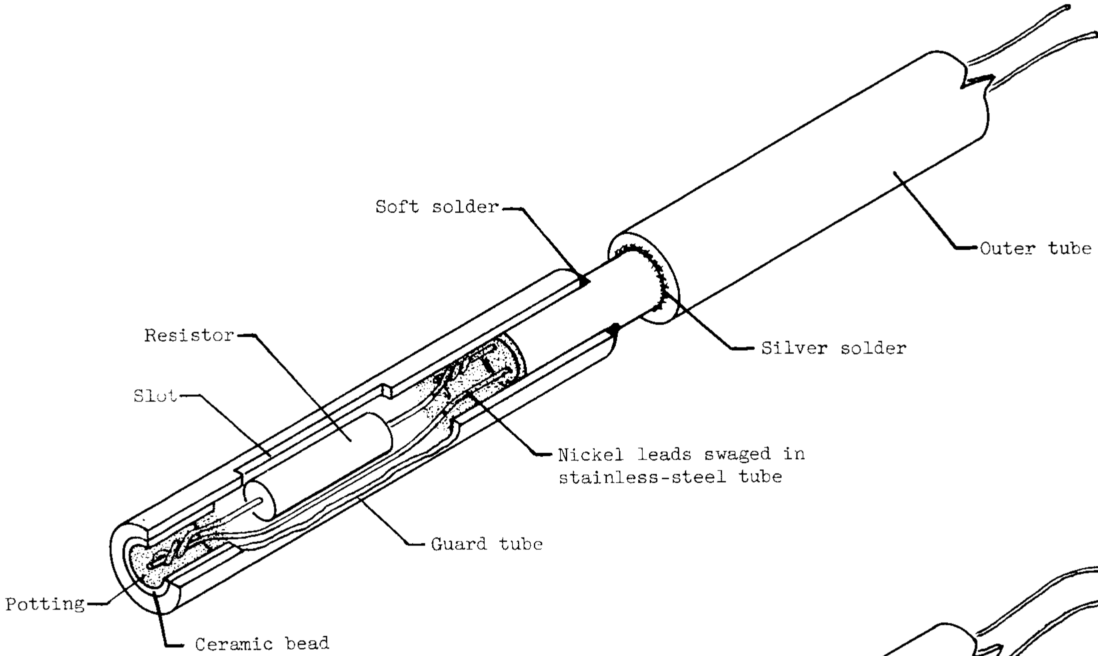
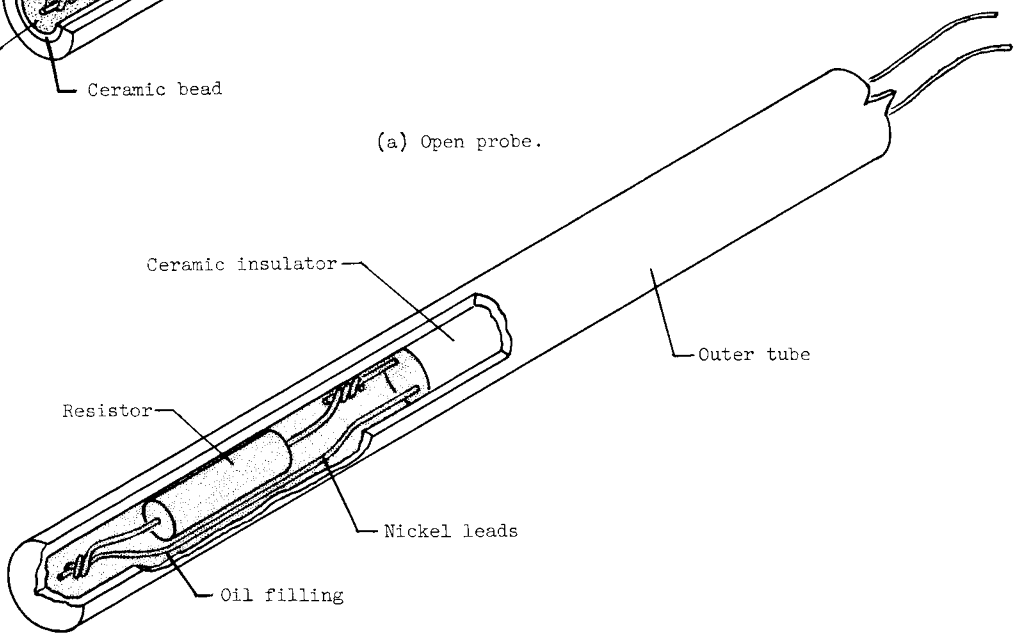


Figure 1. - Apparatus for calibrating resistors.



(a) Open probe.



(b) Closed probe.

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Figure 2. - Probes for mounting resistors.

E-233

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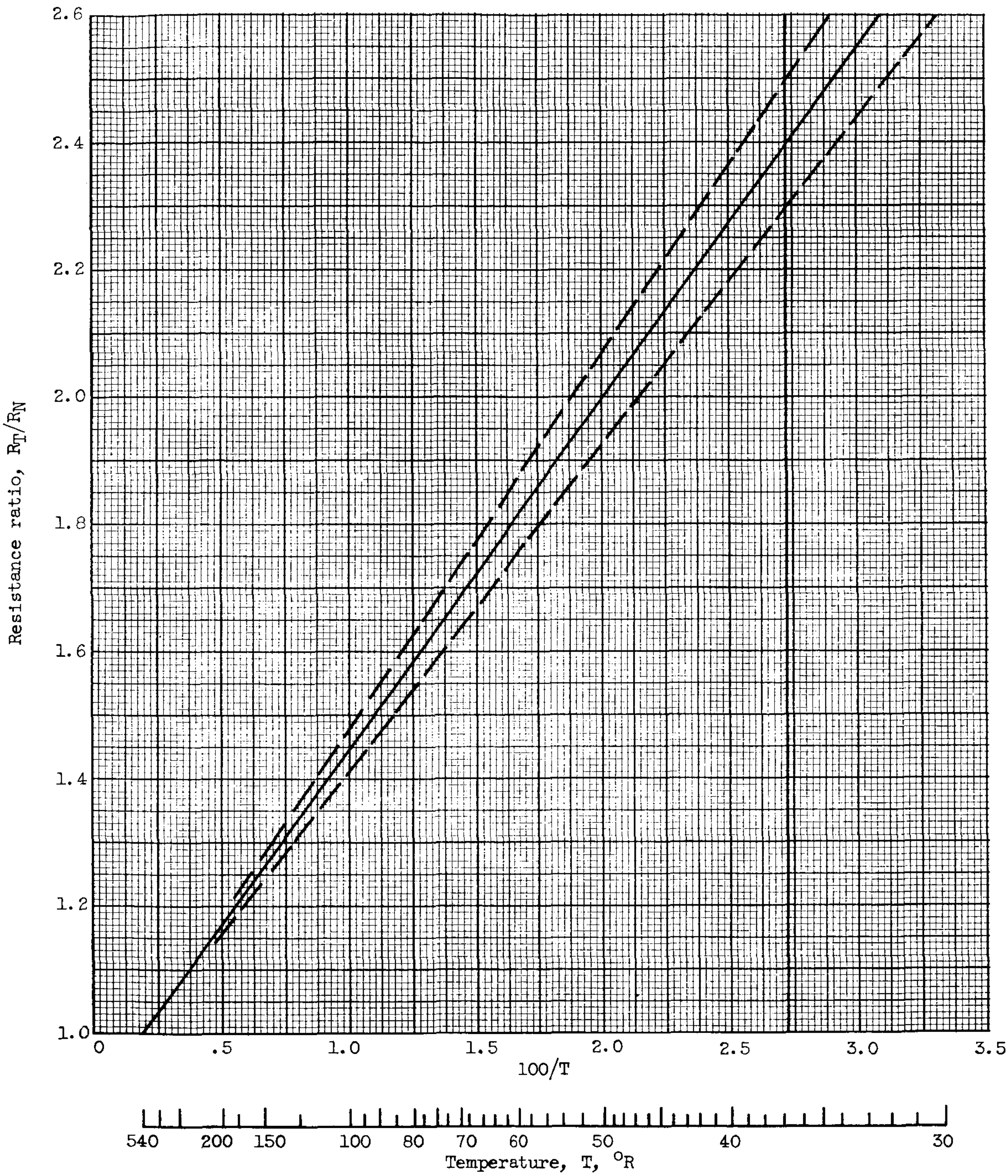


Figure 3. - Variation of resistance ratio with temperature.

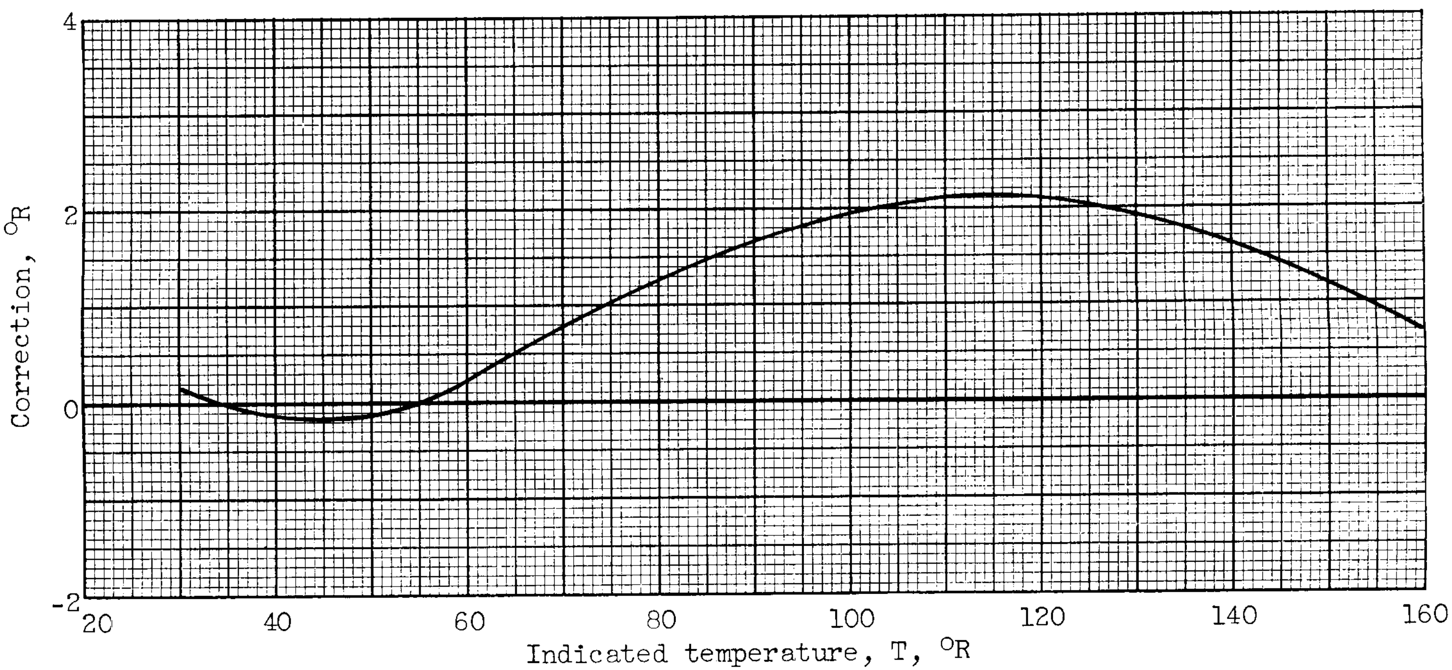
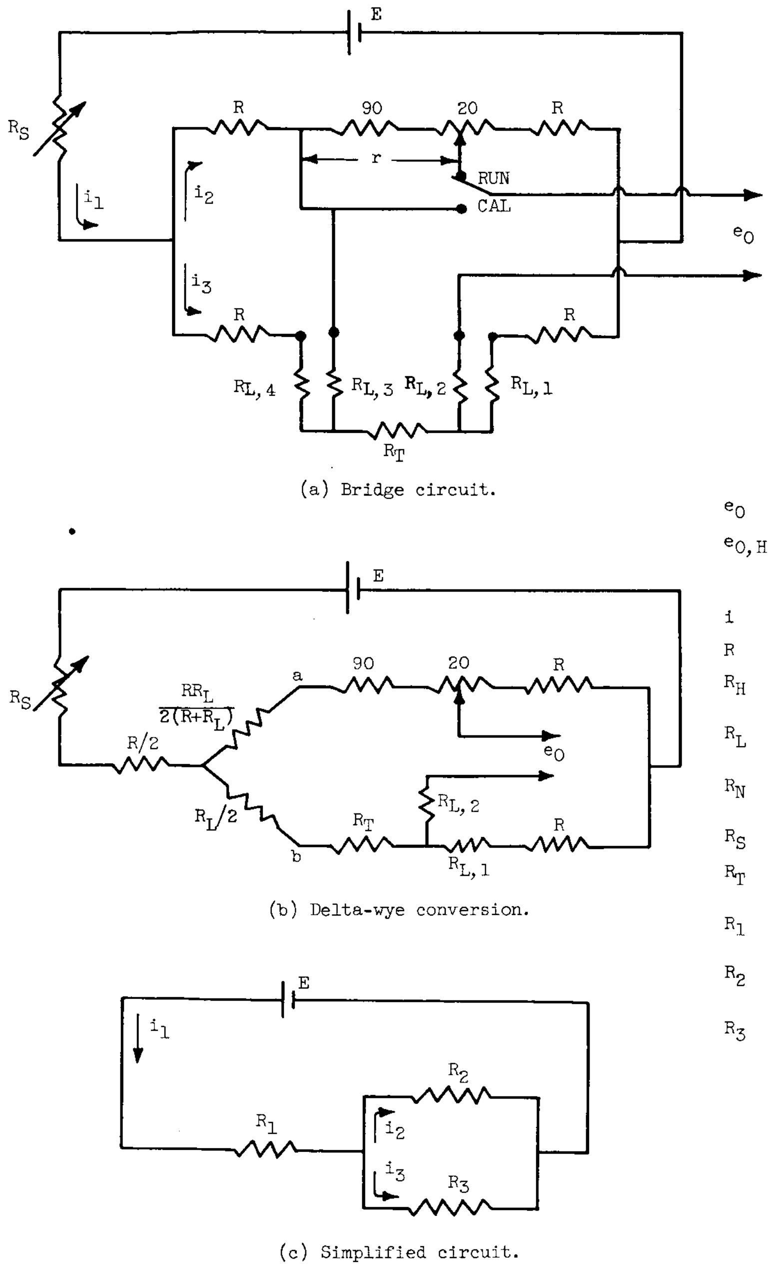


Figure 4. - Average temperature corrections for two-point calibration as shown in figure 3.



e_0	bridge output voltage at temp. T
$e_{0,H}$	output voltage at 36.49° R (b.p. of equilibrium hydrogen at 29.92 in. Hg)
i	current
R	bridge swamping resistor
R_H	resistance of carbon resistor at hydrogen boiling point
R_L	lead resistance of carbon resistor probe
R_N	resistance of carbon resistor at 540° R
R_S	span resistor
R_T	resistance of carbon resistor at temp. T
R_1	$R/2 + R_S \approx R/2$, if $R_S \ll R/2$
R_2	$R + \frac{RR_L}{2(R+R_L)} + 110 \approx R$
R_3	$R + R_T + \frac{3}{2} R_L \approx R$

Figure 5. - Circuit for measuring temperature with carbon resistors.

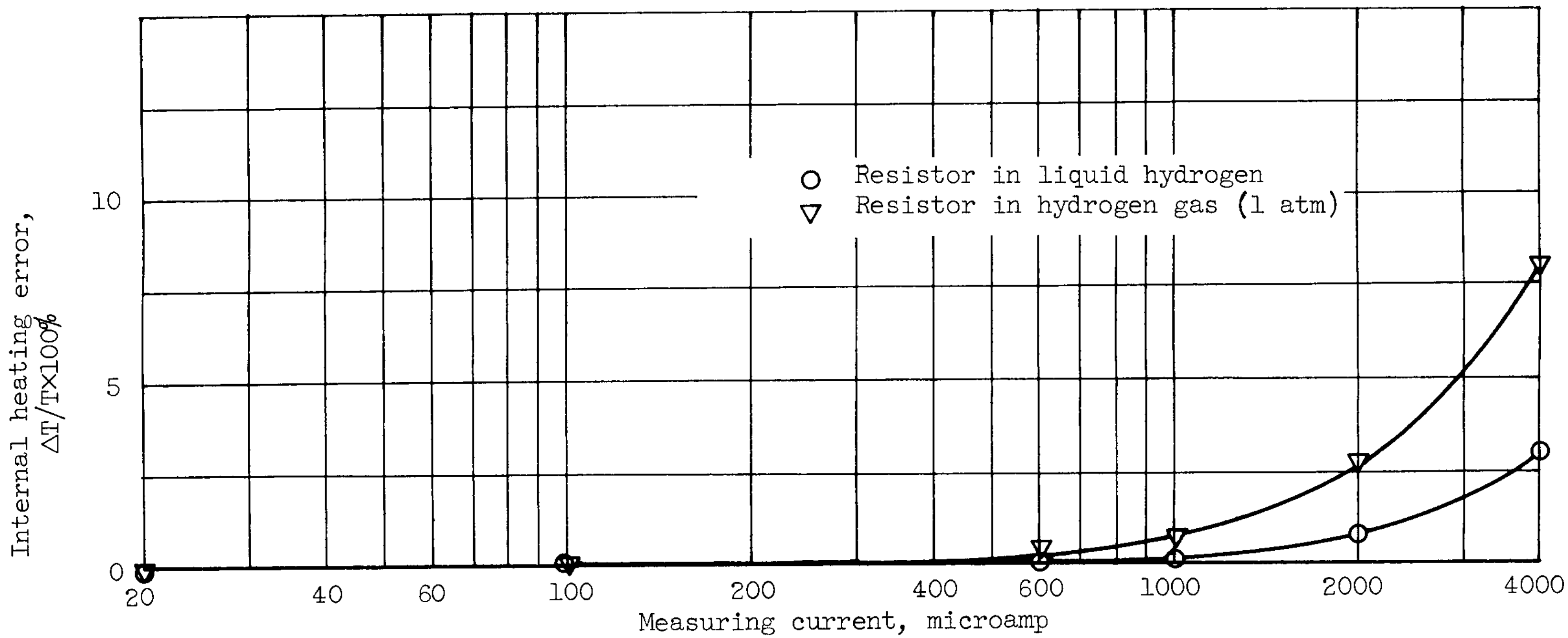


Figure 6. - Variation of internal heating error with measuring current at 37° R and atmospheric pressure.

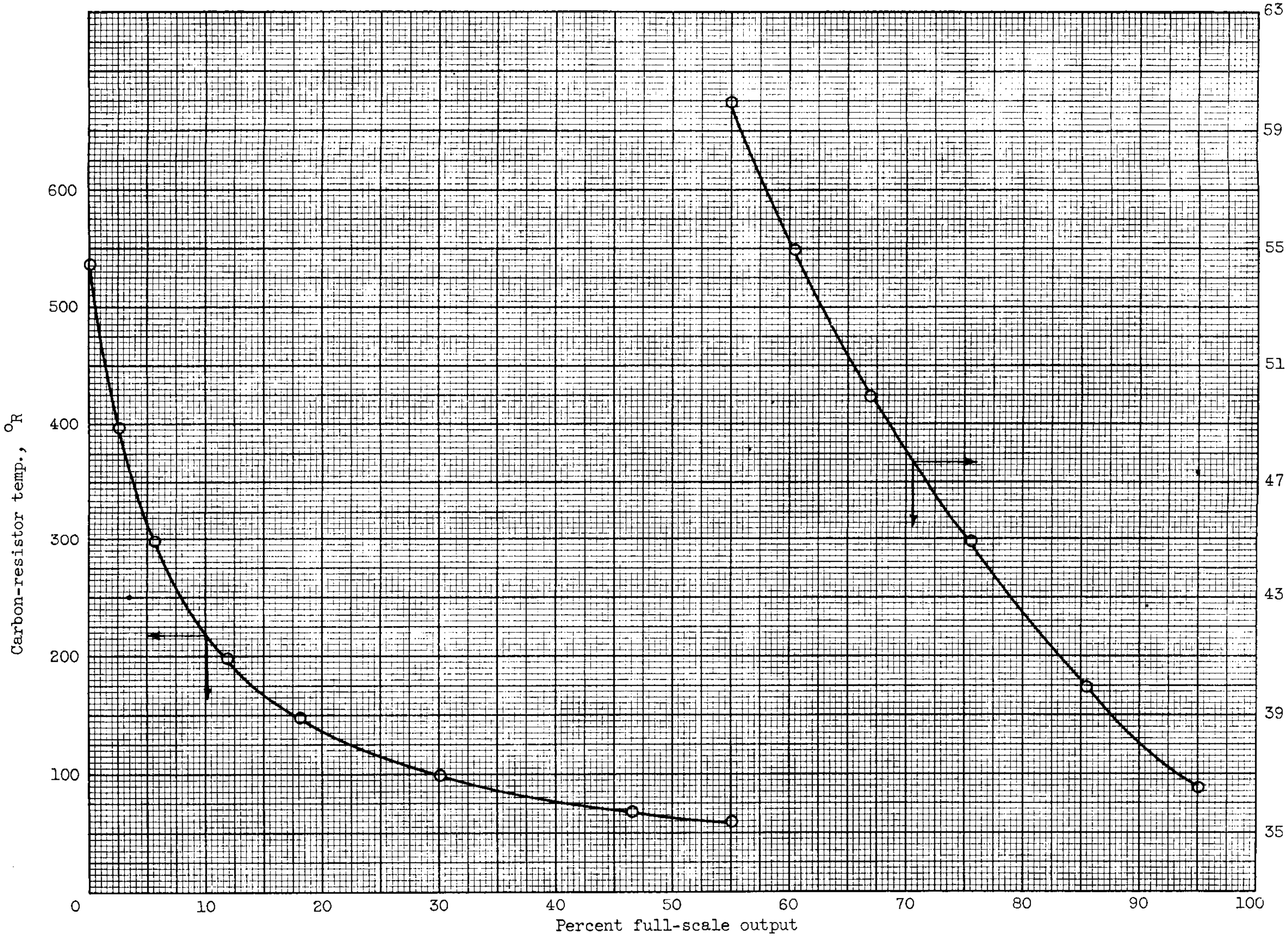


Figure 7. - Variation of carbon resistor bridge output.

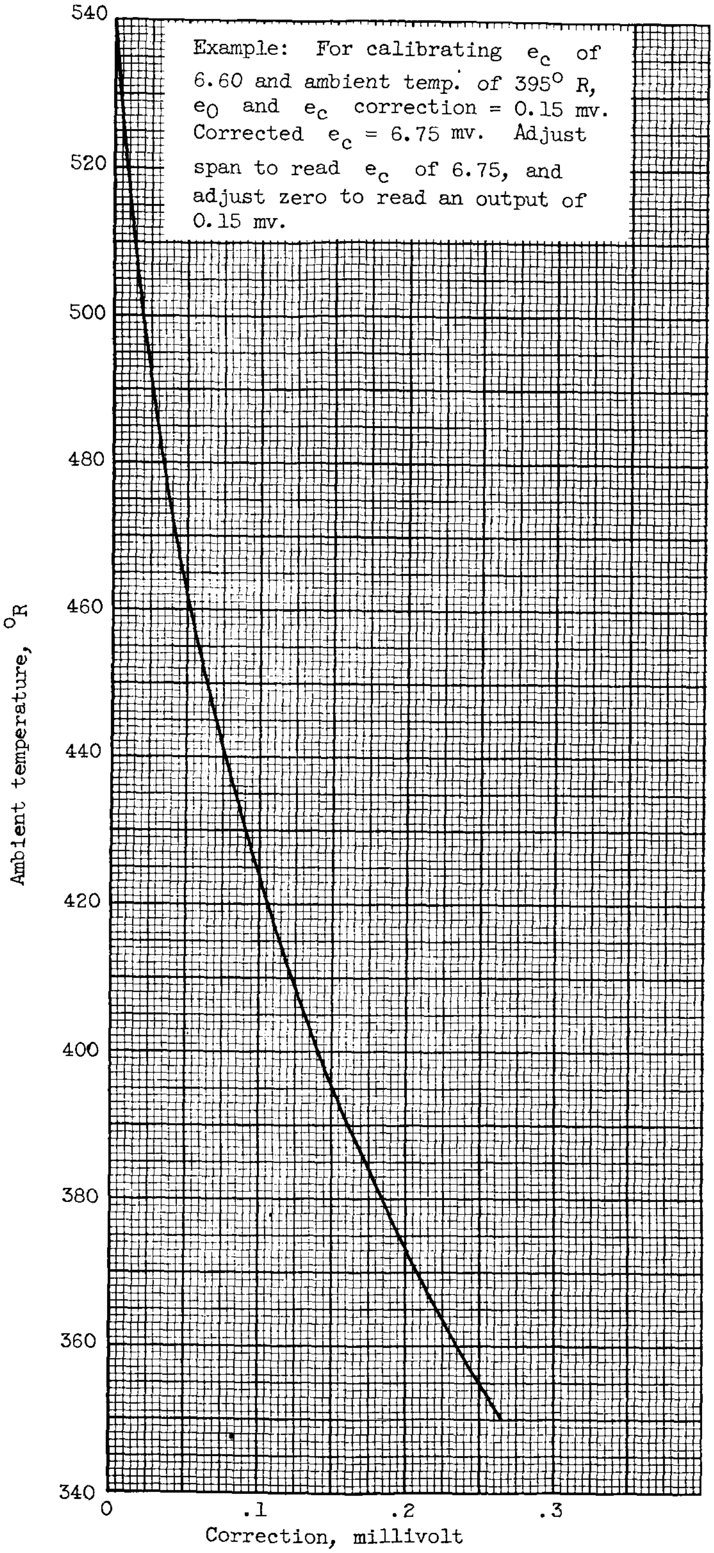


Figure 8. - Calibration emf correction and zero correction against ambient temperature.